

PHASE II FINAL REPORT

VOLUME 1A - PART II
EXECUTIVE SUMMARY

SYSTEM TECHNOLOGY ANALYSIS OF
AEROASSISTED ORBITAL
TRANSFER VEHICLES:
MODERATE LIFT/DRAG (0.75-1.5)

AUGUST 1985

(NASA-CR-179140) SYSTEM TECHNOLOGY ANALYSIS
OF AEROASSISTED ORBITAL TRANSFER VEHICLES.
MODERATE LIFT/DRAG (0.75-1.5): VOLUME 1A,
PART 2: EXECUTIVE SUMMARY, PHASE 2 Final
Report (General Electric Co.) 33 p Avail: G3/16 N87-26063
Unclas 0085381

SUBMITTED TO

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FORWARD

This final report of the "System Technology Analysis of Aeroassisted Orbital Transfer Vehicles: Moderate Lift/Drag (0.75-1.5)" was prepared by the General Electric Company, Space Systems Division for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center (MSFC) in accordance with Contract NAS8-35096. The General Electric Company, Space Systems Division was supported by the Grumman Aerospace Corporation as a subcontractor during the conduct of this study. This study was conducted under the direction of the NASA Study Manager, Mr. Robert E. Austin, during the period from October 1982 through June 1985.

The first phase of this program focused on a ground based AOTV and was completed in September 1983. The second phase was directed towards a space based AOTV and the cryofueled propulsion subsystem-configuration interactions and was completed in March of 1985. The second phase was jointly sponsored by NASA-MSFC and the NASA Lewis Research Center (LeRC). Dr. Larry Cooper was the LeRC study manager.

This final report is organized into the following three documents:

| | |
|------------|--|
| Volume IA | Executive Summary - Parts I & II |
| Volume IB | Study Results - Parts I & II |
| Volume II | Supporting Research and Technology Report |
| Volume III | Cost and Work Breakdown Structure/Dictionary |

Part I of these volumes covers Phase 1 results, while Part II covers Phase 2 results.

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VOLUME IA - PART II

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EXECUTIVE SUMMARY - PART II

1.0 INTRODUCTION

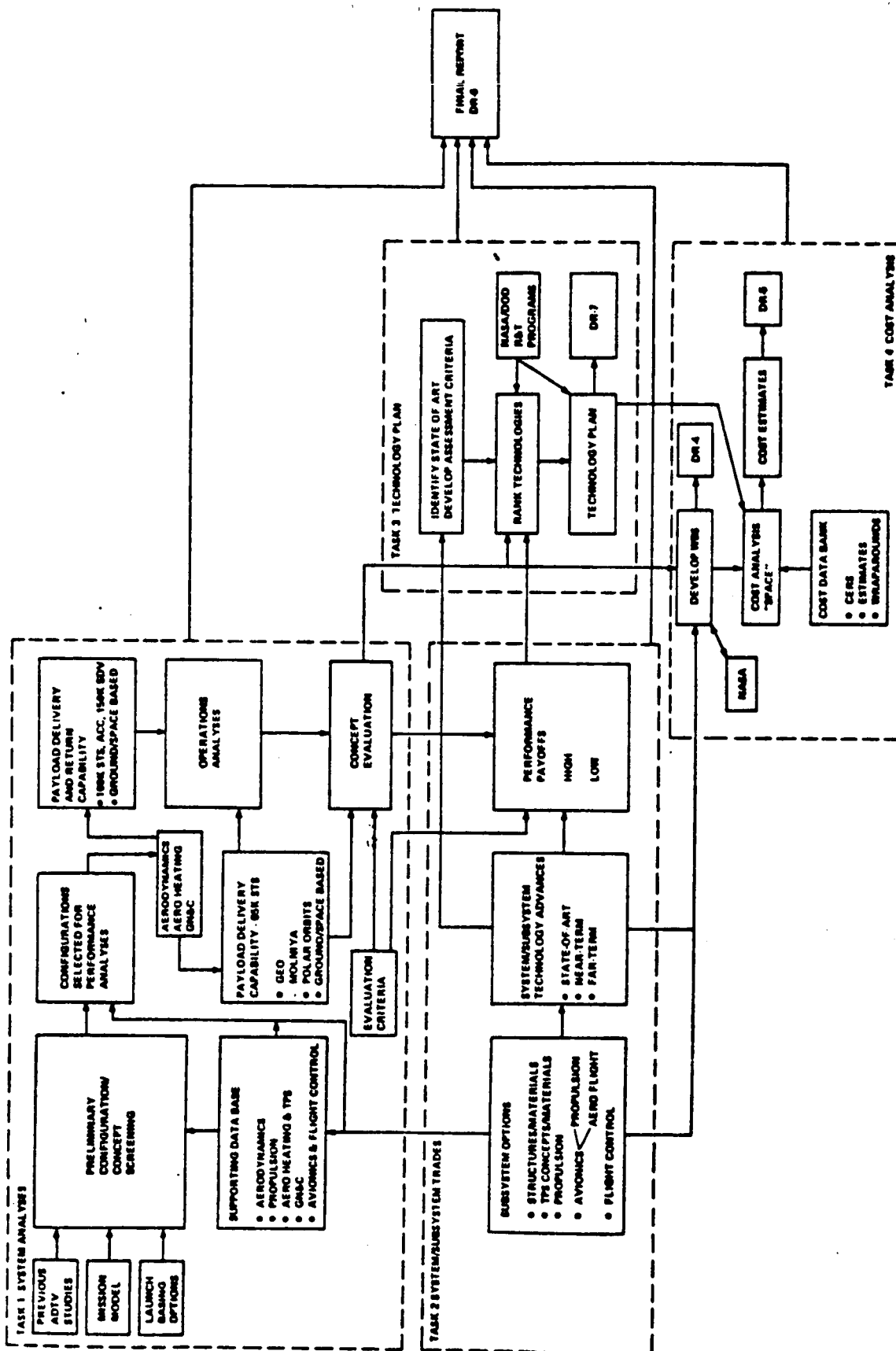
Technology payoffs of representative ground based Mid L/D AOTVs have been assessed and prioritized in Phase I of this study. These results have been summarized in Part I of this final report. Phase II of this study was directed towards identification and prioritization of technology payoffs of representative space based Mid L/D AOTVs and the cryofueled propulsion subsystem - configuration interactions.

Part II of this volume contains a narrative summary of the significant achievements and activities of Phase II of this study. More detailed coverage of the study results are included in Parts II of Volume IB, Volume II and Volume III of this Phase II final report: Study Results, Supporting Research and Technology Report, Cost and Work Breakdown Structure Dictionary.

The major tasks for this portion of the study are outlined in Figure 1-1 as the primary issues confronting the space based Mid L/D AOTV are outlined in Figure 1-2.

Space basing of an AOTV opens up numerous configuration opportunities which were explored in this study. AOTV size can exceed the launch vehicle cargo bay envelope by resorting to assembly in orbit. AOTV stage dry weight or gross lift off weight can exceed the Earth-LEO launch vehicle capability. With the absence of fully fueled tanks, as in the ground based configuration, much lighter gossamer type structures are possible on a Space Based AOTV that may result in performance gains. At the space station, payload rearranging or manifesting may prove attractive.

FIGURE 1-1. MID L/D Φ II STUDY FLOW DIAGRAM



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FIGURE 1-2. SPACE BASED MID L/D AOTV ISSUES

SYSTEMS ISSUES

- o WHAT SIZE AOTV
 - SHAPE/SIZE
 - PAYLOAD DELIVERY CAPACITY
 - UNIVERSAL AOTV VS. UNIQUE DELIVERY AND MANNED VEHICLE VS. ADAPTABLE VEHICLES
- o OPERATIONAL MODE
 - SINGLE STAGE (OPTIONAL USE OF L/D FOR PLANE CHANGE FLYING BELOW OVERSHOOT BOUND)
 - PERIGEE KICK • APOGEE KICK PROPULSION (CAN ALWAYS FLY NEAR OVERSHOOT BOUND)

TECHNOLOGY ISSUES

- o AERODYNAMICS
 - REDUCING W/C_LA TO FLY HIGHER (AND COOLER?)
- o AEROTHERMODYNAMICS
 - TRANSITION TO TURBULENT FLOW (FLY HIGHER TO STAY LAMINAR?)
 - TOTALLY NON-CATALYTIC COATING
 - BASE HEATING TO ENGINE NOZZLES
- o PROPULSION SUBSYSTEM
 - NUMBER OF ENGINES
 - ENGINE THRUST
 - NOZZLE STRENGTH
 - NOZZLE PROTECTION
 - I_{sp}
- o PAYLOAD MANIFESTING
 - AOTV OPERATIONAL MODE
 - AOTV BASING MODE
 - AOTV PREFERRED PROPELLANT SYSTEM
- o SPACE STATION UTILITY
 - PAYLOAD MANIFESTING
 - PROPELLANT STORAGE AND RESUPPLY
- o AOTV MAIN PROPELLANT SELECTION
 - LOX-H₂
 - N₂O₄ - MMH
 - OTHER

SUMMARY OF PHASE II STUDY FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

The major first order findings and conclusions of this portion of the study include the following:

- Automation of routine AOTV inspection and maintenance was identified as the only "enabling" technology for a Space Based AOTV.
- Numerous enhancing technology areas were identified that can provide substantial transport cost reduction. These include 1) improved life time of storable propellant engine, 2) avionics weight reduction, 3) external thermal protection system (TPS) weight reduction by: a) reducing the coating weight, b) further reducing the non-catalytic nature of the coating, increasing the maximum allowable bond/structure temperature, 4) decrease of uncertainties in aerodynamic and aerothermodynamic performance, 5) electrical power subsystem weight reduction due to incorporation of advanced materials and 6) reducing the structural shell weight by improving the quality of the design allowable data and use of advanced structural materials.

System Issues

- Mid L/D aeroassist capability was shown to offer more cost benefit to a reusable state-of-the-art all propulsive stage (Isp = 443 sec.) - \$2.6B, than an advanced space engine (Isp = 480 sec) added to a state-of-the-art all propulsive stage (Isp = 443 sec) - \$1.6B.
- GEO delivery capability of an STS transportable maximum size AOTV which uses a perigee kick delivery mode with apogee kick propulsion (AKP) supplied by the delivered satellite is far in excess of current AOTV mission model requirements. Consequently, there is no need to build such a large AOTV.
- Perigee kick AOTV + AKP produces minimum recurring costs for GEO satellite delivery.
- On re-entry, perigee kick vehicles can fly near one pass overshoot bound to reduce peak surface temperatures.
- Appears to be small advantage of large (vs small) AOTV for cargo transport
- Space based AOTV should be capable of operating from

ground based mode

Aerothermodynamics

- Peak surface temperatures of mid L/D AOTV's are significantly lower
 - Near overshoot bound entry compared to large plane change
 - Totally non-catalytic surface coating compared to partially non-catalytic or fully catalytic surface.
- Substantial uncertainty exists in magnitude of hypersonic base heat transfer and heat transfer to protruding nozzles
 - Current technology suggests minimal nozzle protrusions into separated flow region
 - Advanced technology may provide enlarged allowable zone (CFD, ground tests, calibration of methodology), thus saving substantial TPS and structural aft fuselage weight
 - Flaps should be moved onto body if possible to avoid trailing flap induced shock impingement on nozzles

Aerodynamics

- Space based AOTV's that exceed launch vehicle envelope are not required. Configuration trends of lower total surface area (indicator of weight penalty) and lower surface temperatures (lighter TPS) lead to AMOSS/Biconic type configurations

Propulsion

- Recommendation for advanced LOX-H₂ engines
 - Total Thrust 12-18K LBSF
 - Man rated cargo vehicle - 6-3000 LBF engines
 - Engine gimbal angles should be in the range of 5° to 22°
 - Advanced LOX/Hydrogen engine nozzles have adequate strength for the vibration environment within the Orbiter Cargo Bay.

- o At this time, based on total cost considerations (including space storage), propellant for a cargo transport AOTV - space or ground based, should be earth storable N_2O_4 -MMH

Space Station Technology

- o Payload manifesting (storage and rearranging on AOTV) at Space Station is recommended
- o Space Station propellant manifesting (storage and dispensing to AOTV) is recommended for all propellants except liquid hydrogen

2.1 Overview of Major Results

Building on the configuration trends of our ground-based Phase I study results, namely that the perigee-kick mode always offers maximum performance, and, the observation that off loaded tanks for delivery missions always result in a performance penalty (Figure 2.1-1), a series of modularized, universal (delivery and manned round trip) mid L/D AOTVs were defined for use in our trending and payload manifesting analyses. Examples of these vehicles are illustrated in Figure 2.1-2.

Numerous alternate (non-biconic) classes of configurations were explored to evaluate relative advantages/disadvantages of the bi-conic class of mid/L/D AOTVs. General trends observed in the alternates included larger surface areas - both forebody and base, and much higher local heating rates over the areas of major acreage. These larger surface areas and higher heating rates would result in larger structure and TPS weights, and hence, performance penalties. Consequently, our initial judgment that biconic configurations offer the maximum performance still seems valid, Figure 2.1-3.

2.1.1 Payload Delivery and Performance Evaluation

In the Phase I study, where the AOTV was ground based and thus constrained to fit in the Shuttle payload bay, the sensitivity of delivered payload mass to changes in vehicle dry weight, engine I_{sp} , and available hypersonic L/D were evaluated. Those trends are still valid. However, another parameter, propellant transport cost, was used as a more important trend indicator in this space based portion of the study. Life cycle cost (LCC) analyses have shown that 70-90% of the LCC is attributed to AOTV propellant transport cost. For propellant transport costs of \$1000 per lb to LEO, \$73,000 is saved for each pound of dry mass removed from a perigee kick GEO delivery vehicle and \$6.3M is saved for each second of improvement in engine/propellant I_{sp} . The reader should be cautioned that conclusions drawn from these trending sensitivities may in some cases conflict with those conclusions drawn from a more detailed

FIGURE 2.1-1 TOTAL PROPELLANT REQUIREMENT FOR SEVERAL MID L/D AOTV
GEO DELIVERY MISSIONS

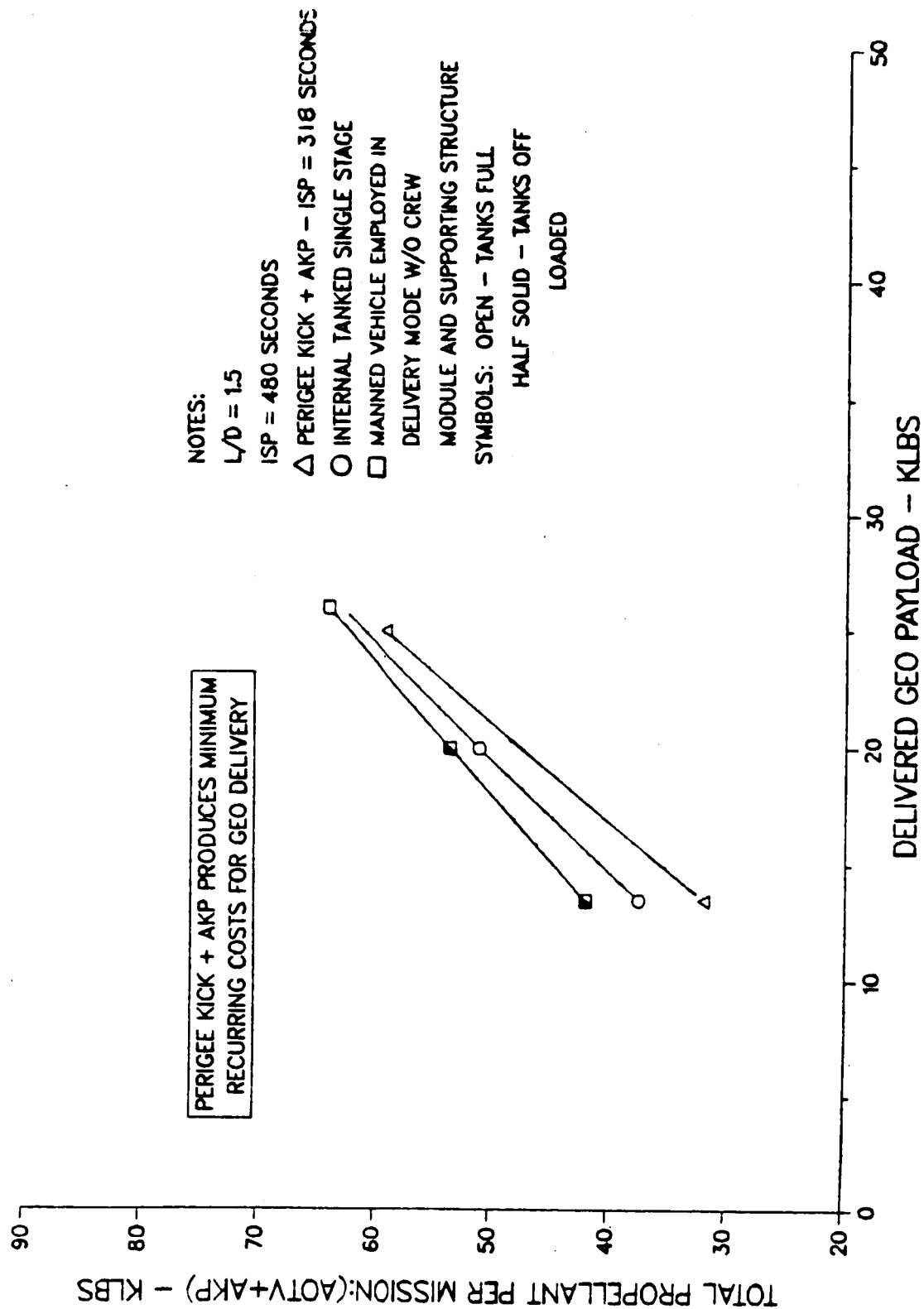
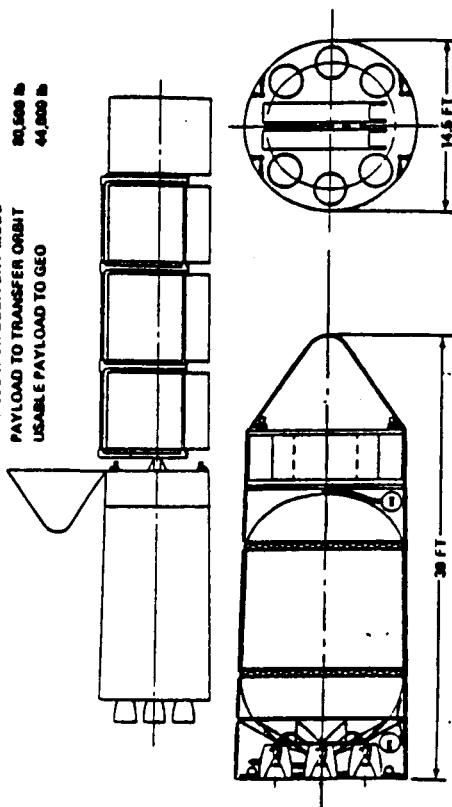


FIGURE 2.1-2. MODULARIZED HHD L/D AOTVS

4 - LO/LH₂/DELIVERY VEHICLE

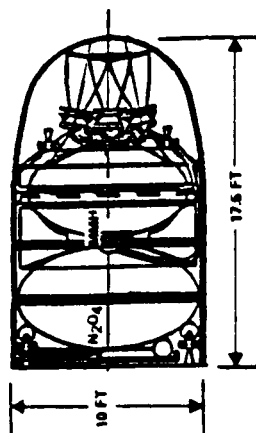
• 1985 TECHNOLOGY AOTV

DRY WEIGHT 7000 lb
 PROPELLANT CAPACITY 65,000 lb
 GLOW 152,500 lb
 PERIGEE KICK DELIVERY MODE
 PAYLOAD TO TRANSFER ORBIT 30,500 lb
 USABLE PAYLOAD TO GEO 44,500 lb



3 - N₂O₄/MMH DELIVERY VEHICLE

DRY WEIGHT 5300 lb
 PROPELLANT CAPACITY 33,000 lb
 GLOW 60,800 lb
 PERIGEE KICK DELIVERY MODE
 • PAYLOAD TO TRANSFER ORBIT 22,300 lb
 • USABLE PAYLOAD TO GEO 12,900 lb



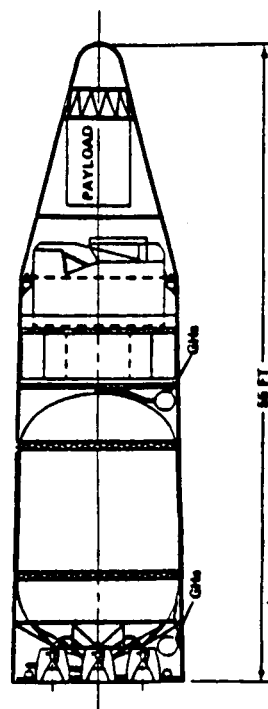
4M - LO₂/LH₂ ORBITER TRANSPORT CONFIGURATION

1985 TECHNOLOGY AOTV

MANNED SERVICE VEHICLE

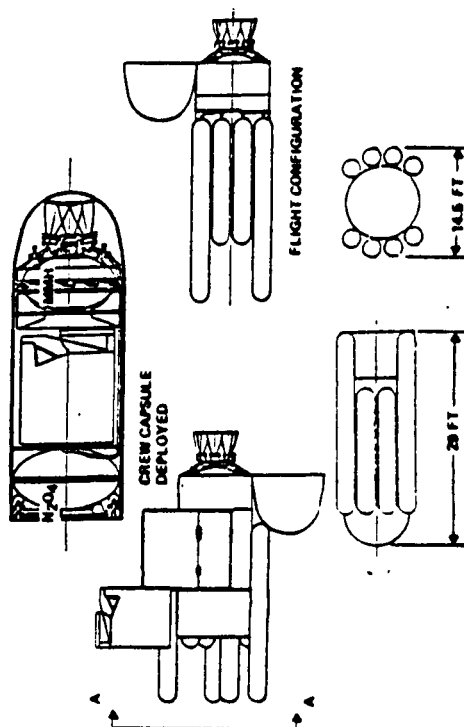
PAYLOAD CAPACITY - 14,000 lb DELIVERED AND RETURNED FROM GEO
 SIX HINGED ENGINES: TOTAL THRUST - 18,000 lbf MR - 7/1
 TOTAL PROPELLANT CAPACITY - 65,000 lb

$g_{sp} = 480 \text{ sec/ft}^2$



3M - N₂O₄/MMH MANNED VEHICLE

DRY WEIGHT 13,700 lb
 PAYLOAD LEFT AT GEO 1800 lb
 DROP TANK WEIGHT & PLUMBING 900 lb
 PROPELLANT CAPACITY 90,000 lb
 MAIN TANKS 32,000 lb
 AUXILIARY TANKS 57,000 lb
 GLOW 106,400 lb

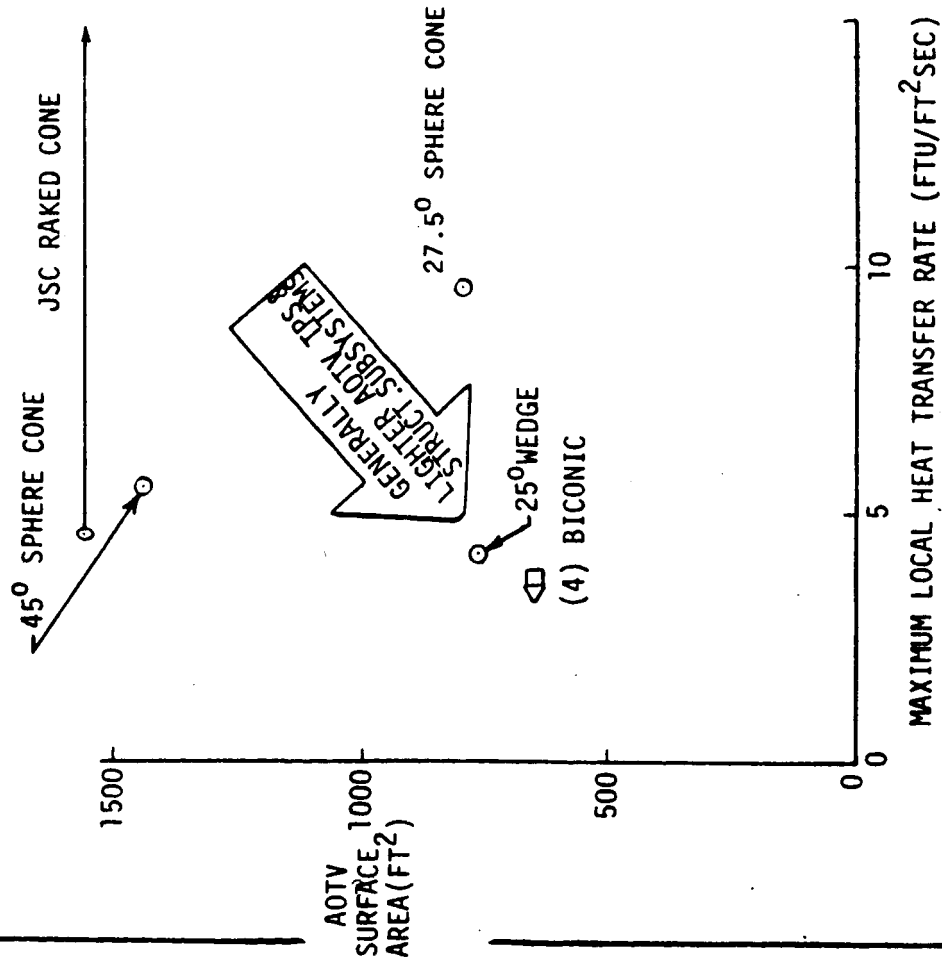


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RE-ENTRY SYSTEMS OPERATIONS

FIGURE 2.1-3
SPACE BASED AOTV CONFIGURATION CONCLUSIONS



- o SMALLER SURFACE AREA MINIMIZES TPS + STRUCTURE WEIGHT
 - o LOWER HEAT TRANSFER ON MAJOR AREA IS GOOD
 - o FLIGHT PROVEN AERODYNAMICS
- ↑
- IMPROVED PERFORMANCE
- ↑
- LOWER COST

BICONIC CLASS IS BEST
FOR SPACE BASED
MID L/D AOTV

payload manifesting study.

Prior studies at Grumman* have indicated that OTV propellant mass was not the determining factor in the cost of transporting OTV propellant from Earth to LEO (which is virtually 100% of propellant transport costs, since acquisition of propellant is on the order of \$2/pound). Rather, these prior studies indicated that packaging (or manifesting) propellant and other cargos within the Orbiter's Cargo Bay, where both length and weight (i.e., propellant density) are factors which influence the cost of transport, was the determinate of transport costs. At this time (1983), a rough transport cost equivalence was established between two OTV systems for delivering an entire mission model. The two OTV systems were space based, all propulsive OTVs which utilized two very different propellants: a storable OTV using N_2O_4 /MMH with a specific impulse of about 340 seconds, and, a cryogenic OTV using LOX/Hydrogen with a specific impulse of 460 seconds. The manifesting study indicated that the additional propellant mass needed by the lower performing storable did not cost the US government more STS flights, since the higher density storable propellant fit better into available open spaces in the STS cargo bay. Consequently, both cryogenic and storable systems required about the same number of STS flights. Results similar to these were achieved in this study.

To understand the transport cost implications of the large variety of options for AOTV configurations, propellants, operating modes and basing modes, as well as to determine their impact on Space Station, a computer program was developed at Grumman under IR&D sponsorship to perform manifesting studies. This proprietary program was used during this Phase II study to determine which new propulsion technologies offered significant benefit to the US government and its AOTV program. The method used a NASA Mission Model** for 1995 through 2000, with all Earth to LEO transport via STS orbiter. The six year mission model contained AOTV Earth to LEO payloads (AOTVs, AOTV payloads and AOTV propellant) plus 180 NASA Earth to LEO payloads (OMVs, OMV propellant, Space Station Modules, Space Station payloads, LEO satellites, GEO satellites, Polar and GEO platforms and their payloads, and unmanned missions). The output of the computerized manifesting study is the number of STS flights required to deliver the entire mission model to LEO (including one type of

* The results were reported during the Phase A Space Station Studies (1983). The underlying manual manifesting analysis was never disclosed in public.

** Published by Space Station Working Group, Summary of 1984. The model was augmented by GAC Space Station Program personnel.

AOTV and its propellants). Thus, at a cost of \$84M to \$100M per marginal STS flight, by comparing the number of STS flights required by AOTV System A with the number of STS flights needed by AOTV System B, an estimate is available for the actual cost to the US government of choosing AOTV system A vs. B. Consequently, we have selected the difference-in-numbers-of-required-STS-flights as the first order of magnitude tool in evaluating economics and performance of competing AOTV systems.

2.1.2 Propellant Transport Costs

During this study, we have approached this subject from two different directions. To support a variety of trending analyses, we estimated a cost of delivering propellants to Space Station from a dedicated Orbiter flight. Our studies utilized an enhanced capability orbiter which is capable of delivering 65,000 pounds of cargo to a Space Station orbit, or, about 61,000 pounds of propellant on a dedicated flight. This implies a delivery cost (at \$84.4M per STS flight) of \$1380/pound of propellant. Some transport cost reductions from propellant scavenging from the STS external tank, as well as occasional deliveries to LEO of propellants within open spaces of the STS Cargo Bay, were considered. These reductions produced a propellant transport cost of approximately \$1000/pound, the value used in our trending analyses.

The manifesting study did not consider a value for propellant transport costs. The study results seem to imply that different propellant systems, because of the different densities and amounts required, have very differing propellant transport costs. In general, it appears as if the cost of delivering marginal propellant to handle AOTV weight increases on the order of 10% are relatively small - on the order of \$15M/year, or \$2M per AOTV flight,

2.1.3 AOTV Technology Payoffs

A detailed review of the current state-of-the-art in the various technology and subsystem areas was conducted in the ground based Phase I portion of this study and was summarized in Volume II. A number of improvements, resulting in from 10-70% reduction of subsystem dry weight, were identified and summarized in Figure 2.1-5 of Part I of this volume. Other improvements/issues in some cases more difficult to quantify have been summarized in Figure 2.1-8 of Part I of this volume. Some of the more significant, worthy of mention, include structure and TPS weight reduction due to improved materials and design methodology, improved propulsive I_{sp}, avionics weight reduction due to miniaturization, vehicle aerodynamic and boundary layer transition uncertainties, and trailing flap/body shock interacting flow fields and heat transfer amplification.

Various techniques exist for ranking technology benefits. The method selected for this space-based portion is as follows: given a subsystem weight reduction or other performance improvement possibility, the effect on AOTV propellant transport cost was determined for a generic delivery (10 flights per year for ten years) and manned round trip (2 flights per year for ten years) mission model. The technology payoffs are then rank-ordered in decreasing propellant transport cost.

The mid L/D performance sensitivities have been combined with the subsystem weight reduction possibilities to generate the propellant transport cost reductions summarized in Table 2.1-1. It is instructive to compare the mid L/D AOTV vehicles to all propulsive missions. All propulsive stages have been created by removing the TPS and nose fairing from the mid L/D vehicles. Illustrated here in Figure 2.1-4 in trending analyses, is the total propellant transport cost for all propulsive OTV's with state-of-the-art cryofueled $I_{sp} = 443$ sec and advanced technology versions with $I_{sp} = 460$ and 480 sec. Also compared in this all delivery scenario is the advantage of using the hypersonic L/D for orbital plane change and the advantage of using a perigee kick scenario in contrast to a single stage operation. Note that aeroassist provides a clear operational cost advantage over the all propulsive OTV; perigee kick + AKP provides a clear advantage over single stage operation; and use of a stripped manned vehicle off-loaded for GEO delivery incurs substantial penalty. The propellant transport costs have been evaluated to determine the incremental cost advantage of several different combinations of aeroassist or advanced technology. These cost advantages are summarized in Table 2.1-2. Note the clear indication that introduction of aeroassist to a current technology engine provides a larger cost impact than introduction of an advanced technology engine in an all propulsive OTV. Numerous other interesting comparisons have been made and are illustrated. Payoffs (exclusive of costs) for aeroassist and/or new small high I_{sp} engines exceed \$1 billion. Note also that the individual technology payoff areas are generally at least an order of magnitude less important than some of these systems considerations.

Other technology advance benefits in the areas of aerodynamics, aerothermodynamics, and GN&C were identified in Phase I of this study. These benefits are still applicable to Phase II of this study but a bit more nebulous to quantify. They will be carried in the recommended technology list at a location consistent with their Phase I ranking. The technology priority listing is summarized in Table 2.1-3.

A survey was conducted of NASA LaRC, JSC, and ARC in October of 1984 to ascertain their perceptions of AOTV Technology Needs. The 1982 Aeroassist Working Group Technology Development

TABLE 2.1-1 SPACE BASED MID L/D AOTV
TECHNOLOGY PAYOFFS
ENHANCING TECHNOLOGY
IN ORDER OF IMPORTANCE

| SUBSYSTEM AREA | Δ TOTAL PROPELLANT TRANSPORT COST @ \$1000/LB | | |
|--|--|---|---|
| | PERIGEE KICK DELIVERY (100 FLIGHTS) M\$ | MANNED 14 UP & BACK (20 FLIGHTS) M\$ | DELIVERY + MANNED (120 FLIGHTS) M\$ |
| INCREASED I_{sp} | 234 | 217 | 451 |
| AVIONICS WEIGHT REDUCTION | 25-34 | 19-27 | 44-61 |
| EXTERNAL TPS DESIGN | 17 | 27 | 45 |
| ELECTRICAL POWER SUBSYSTEM WEIGHT REDUCTION | 10-18 | 8-15 | 18-33 |
| STRUCTURE WEIGHT REDUCTION SPACE BASED VS GROUND BASED | 6-18 25 | 3-8 11 | 9-26 35 |

FIGURE 2.1-4 SPACE BASED CRYOGENIC PROPELLANT TRANSPORT COSTS
FOR REUSABLE OTV GEO DELIVERY

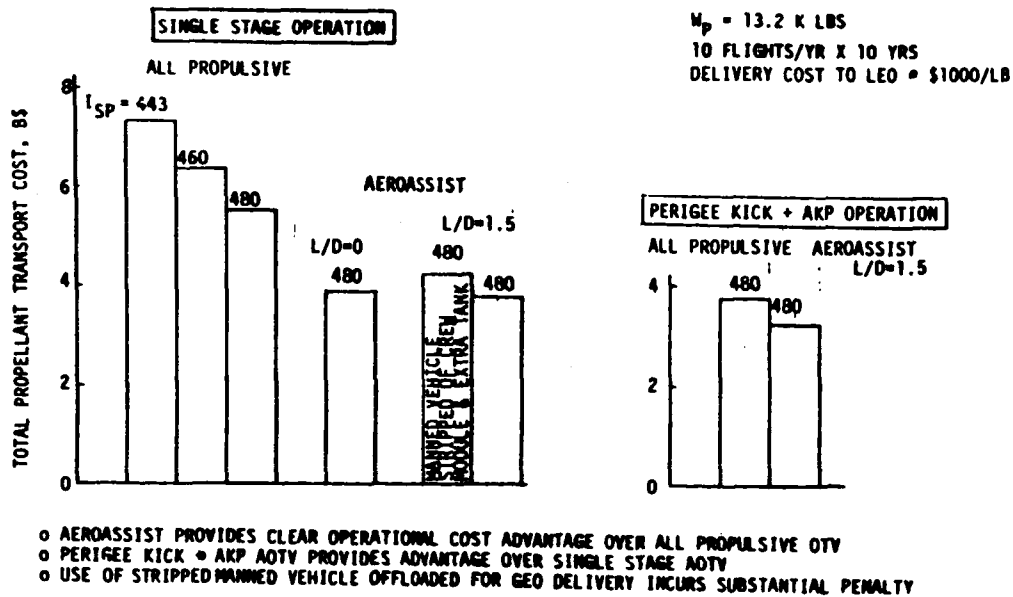


TABLE 2.1-2. SPACE BASED MID L/D AOTV SYSTEM PAYOFF

WP/L = 13.2 KLBS
 10 FLTS/YR X 10 YRS
 DELIVERY COST TO LEO = \$1000/LB

| | <u>COST SAVINGS</u> (B\$) |
|---|------------------------------|
| (1) ADD NEW ENGINE AND AEROASSIST (OPERATE @ L/D = 1.5) TO ALL PROPULSIVE SINGLE STAGE ($I_{sp} = 443$) | 3.55 |
| (2) ADD AEROASSIST (OPERATE MID L/D @ L/D = 0) TO ALL PROPULSIVE SINGLE STAGE ($I_{sp} = 443$) | 2.6 |
| (3) ADD NEW ENGINE ($I_{sp} = 480$) TO ALL PROPULSIVE SINGLE STAGE ($I_{sp} = 443$) | 1.8 |
| (4) ADD AEROASSIST (OPERATE MID L/D @ L/D = 1.5) TO ALL PROPULSIVE SINGLE STAGE ($I_{sp} = 480$) | 1.6 |
| (5) ADD NEW ENGINE TO SINGLE STAGE MID L/D AOTV (OPERATE @ L/D = 0) | 0.8 |
| (6) ADD AEROASSIST (OPERATE @ L/D = 0) TO ALL PROPULSIVE PERIGEE KICK STAGE ($I_{sp} = 480$) | 0.53 |
| (7) ADD NEW ENGINE ($I_{sp} = 480$) TO ALL PROPULSIVE PERIGEE KICK STAGE ($I_{sp} = 443$) | 0.32 |

TABLE 2.1-3. SPACE BASED MID L/D AOTV TECHNOLOGY PRIORITIES

| <u>MISSION ENABLING TECHNOLOGY</u> | |
|--|--|
| AUTOMATION OF ROUTINE INSPECTION & MAINTENANCE | |
| <u>MISSION ENHANCING TECHNOLOGY</u> | |
| <u>PRIORITY</u> | <u>ITEM</u> |
| 1 | IMPROVED LIFE TIME OF STORABLE PROPELLANT ENGINE |
| 2 | AVIONICS WEIGHT REDUCTION + GN&C |
| 3 | EXTERNAL TPS DESIGN |
| 4 | AERODYNAMIC KNOWLEDGE |
| 5 | AEROTHERMODYNAMIC KNOWLEDGE |
| 6 | ELECTRICAL POWER SUBSYSTEM WEIGHT REDUCTION |
| 7 | STRUCTURE SUBSYSTEM WEIGHT REDUCTION |

Plan was used as a basis for discussing their current R&T Programs and Plans in a series of working meetings at the various centers. As a result of this series of meetings, an updated draft version of the AOTV Technology Development Plan was generated and a list prepared of those Technology Areas that we perceived to need supplemental emphasis/funding, Table 2.1-4.

A detailed Technology Plan was prepared as a part of Phase I of this study, Volume II, and has been supplemented with several additional technology items as a result of this study.

2.1.4 Space Station Technology Payoffs

The manifesting study was used to determine the economic benefit of the addition of two technologies to a Space Station: AOTV payload manifesting and AOTV propellant manifesting. The study compared the effects of 3 different AOTV ground basing modes, each with differing amounts of Space Station involvement in the AOTV mission. Four different AOTVs, using 4 different propellant systems, were evaluated. The results were very similar for all 4 propellant types.

Over the 6 year mission model, which required about 90 STS flights, an average of 2 STS flights were saved by adding Space Station manifesting of AOTV payloads. Although the number of eliminated STS flights is small, it represents a savings on the order of \$200M over 6 years. This \$200M savings will greatly exceed the cost to Space Station for providing for AOTV payload manifesting, since most of the necessary structure and machinery will be in place for (and paid by) Space Station needs. Consequently, this new technology is recommended for AOTV operations.

An average of 4 to 5 STS flights were saved (over 6 years) by adding Space Station manifesting of AOTV propellants to the SS system which manifests AOTV payloads. Although these approximately \$500M savings are larger than those for payload manifesting, the costs to Space Station for providing propellant manifesting are very significant. A crude rough order of magnitude (ROM) cost estimate indicated that, for all propellants under consideration except LOX-Hydrogen, the dollar benefit of reduced STS flights (approximately \$500M) exceeded the cost of providing this service. Since a LOX-Hydrogen storage and dispensing system is estimated to cost over \$300M more than the benefit it will provide, LOX-Hydrogen is not recommended for SS propellant manifesting. Because most of the infrastructure necessary for storage and dispensing N_2O_4/MMH will be in place at SS to service the OMVs, the additional cost to handle an AOTV will be the smallest of all propellant systems under consideration. Consequently, N_2O_4/MMH is the recommended AOTV propellant for Space Station propellant manifesting.



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FIGURE 2.1-4 TECHNOLOGY AREAS NEEDING SUPPLEMENTAL FUNDING

- DEVELOPMENT OF LESS CATALYTIC THERMAL PROTECTION MATERIALS COATINGS
- TPS/STRUCTURAL DESIGN - EVALUATE NEW STRUCTURAL MATERIALS AND BOND SYSTEMS OPERATING AT HIGHER SOAK OUT TEMPERATURES
- DESIGN, FABRICATE AND TEST TRANSPIRATION COOLED NOSE WITH SEEDED COOLANT
- AEROTHERMODYNAMIC METHODOLOGY - LEESIDE AND BASE AREA HEAT TRANSFER AND WAKE CLOSURE
- AUTOMATION OF HEALTH MONITORING, INSPECTION AND ROUTINE MAINTENANCE
- PAYLOAD MANIFESTING ACROSS MISSION MODEL TO EVALUATE CRYO VS. STORABLE PROPELLANT TRANSPORT ADVANTAGES/DISADVANTAGES
- GN&C - OPTIMIZATION OF A HYBRID FLIGHT CONTROL MECHANISM THAT BLENDS THE AERODYNAMIC AND REACTION CONTROL SUBSYSTEMS ON A LIFT MODULATED AOTV
- AVIONICS - EVALUATION OF INERTIAL INSTRUMENT DEVELOPMENT AND PERFORMANCE, PROVIDE DIRECTION TO INSTRUMENT CONTRACTORS
- N_2O_4 - MMH ENGINE NEEDS NOT EVALUATED DURING THIS STUDY

2.1.5 Attractive Space Based AOTV Configuration Approaches

Space basing of AOTV offers the possibility of AOTV sizes and shapes which exceed the confines of Earth to LEO launch vehicles like STS orbiter. We investigated some configuration possibilities offered by space basing. All had larger surface areas than a biconic, and would require heavier structural and thermal protection subsystems than our baseline vehicles. In fact, biconic AOTVs which occupy more than half of an Orbiter's Cargo Bay (i.e., AOTV length >30') produce vehicles whose GEO payload delivery capacity greatly exceeds currently projected needs (40 + 90K lbs). These trends indicate that compact, minimum size AOTVs are preferable for high performance (i.e., pounds of payload per pound of propellant).

When economic considerations were merged with performance considerations in a manifesting study, slightly different conclusions were reached. For a fully space based AOTV, our largest man-rated vehicle (used in an unmanned cargo carrying role) with 18,000 lb of thrust was compared with a much smaller AOTV (lighter by 1275 pounds = 18%) with 9000 lb of thrust, Figure 2.1-5. Both AOTVs required the same number of STS flights to perform the mission model. However, the larger vehicle is less expensive to operate:

- Fewer AOTV flights
- No need for external tankage on "large payload" flights

Consequently, our recommendations for a fully space based AOTV are

- 1) Internal propellant tankage should be sized for the largest task in the mission model.
- 2) Total vehicle thrust should be sized for the large vehicle and large payload
 - On the order of 18,000 lb_f for the mission model we studied

These recommendations are undermined by another manifesting study result. Figure 2.1-6 displays a comparison of lightweight AOTVs designed for only space based operation with heavier (approximately 570 lb = 10%) very short AOTVs designed for ground based operations. The results show an average of only 1 STS flight saved by the lighter vehicles over a 6 year period. This savings of approximately \$100M precludes use of the AOTV in a ground based mode, implying that service to military orbits at inclinations of 63°, 90°, and 98° must occur from a 28-1/2° inclination Space Station, or from a separate ground based

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FIGURE 2.1-5. 4M - LO₂/LH₂ ORBITER TRANSPORT CONFIGURATION

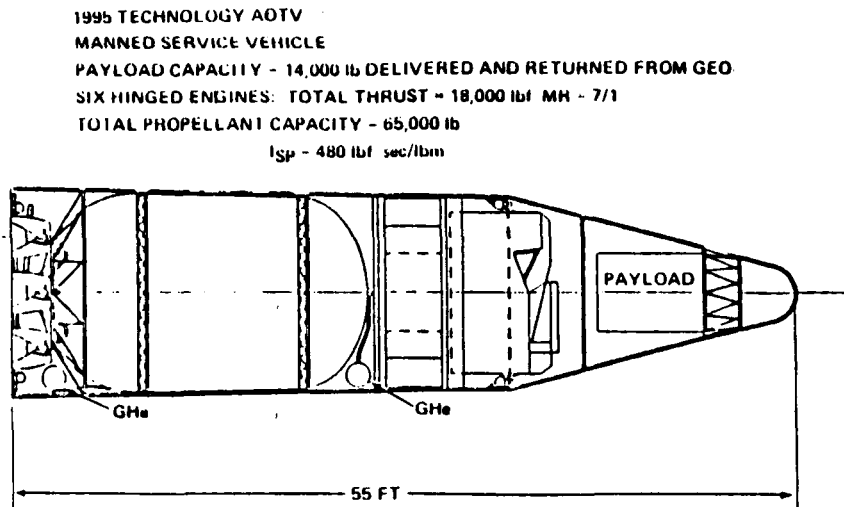


FIGURE 2.1-6. STUDY RESULTS: STRONG vs "GOSSOMER" SB OTV

- ISSUE: SHOULD SPACE BASED OTV BE STRONG ENOUGH TO OPERATE AS GROUND BASED, OR, SHOULD SB OTV BE MIN WEIGHT (FROM MIN STRENGTH) AND USE LESS PROPELLANT?
- STUDY COMPARED 4 PAIRS OF OTV, EACH PAIR USED SAME PROPELLANT
 - GB OTV USED IN SB MODE
 - SB OTV USED IN SB MODE
 - ALL VEHICLES FLEW PERIGEE KICK OPERATIONS MODE

| VEHICLE | Δ DRY WT | # OF STS FLTS | Δ # OF STS FLTS | } INSIGNIFICANT OVER 6 YEARS |
|--|----------|---------------|-----------------|---------------------------------|
| 10-LO ₂ /LH ₂ | +575 LB | 86 | +1 | |
| 11-LO ₂ /LH ₂ | | 85 | | |
| 3-LO ₂ /MMH | +575 LB | 94 | +1 | |
| 4-LO ₂ /MMH | | 93 | | |
| 7-N ₂ O ₄ /MMH | +550 LB | 98 | +2 | |
| 8-N ₂ O ₄ /MMH | | 96 | | |
| 6-N ₂ F ₄ /N ₂ H ₄ | +580 LB | 91 | -1 | |
| 7-N ₂ F ₄ /N ₂ H ₄ | | 92 | | |

- CONCLUSIONS
 - SERVICING MILITARY PAYLOADS IN POLAR ORBITS (GS FROM VAFB) WITH NASA OTV IS MORE IMPORTANT THEN THE SMALL NUMBER OF STS FLIGHTS SAVED BY SUPER LIGHT STRUCTURE ON OTV

military OTV. The cost of both of these alternatives will greatly exceed the projected savings. Consequently, we recommend that the next generation AOTV be capable of efficiently operating in a ground based mode, in addition to its utilization of a space base.

2.1.6 Alternate AOTV Propellants

An examination of a variety of candidate OTV propellants (suggested in other studies) was conducted. The idea that propellant density (ρ) might be as important as propellant performance (I_{sp}) was explored, since both packaging within the Orbiter and within a biconic aeroshell will be influenced by propellant density. The broad range of propellants considered, and the figure of merit used for first selection (ρI_{sp}), are shown in Table 2.1-5. Four propellants were evaluated in the manifesting study:

- o Tetrafluorohydrazine/Hydrazine - N_2F_4/N_2H_4
- o Liquid Oxygen/Liquid Hydrogen - LO_2/LH_2
- o Nitrogen Tetraoxide/Monomethylhydrazine - N_2O_4/MMH
- o Liquid Oxygen/Monomethylhydrazine - LO_2/MMH

TABLE 2.1-5. **COMPARISON OF AVAILABLE PROPELLANTS**

| PROPELLANT COMBINATION | N_2F_4/N_2H_4 | LO_2/LH_2 | N_2O_4/MMH | LO_2/MMH | LO_2/C_3H_8 | LO_2/CH_4 |
|---|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| *DENSITY IMPULSE lbf sec/ft ³ | 35203 ² | 29308 ¹ | 26788 ¹ | 24043 ² | 23594 ² | 22949 ² |
| *SPECIFIC IMPULSE lbf sec/lbm | 383 ² | 480 ¹ | 343 ¹ | 373 ² | 378 ² | 381 ² |

*AT E = 400/1 and I_{sp} MAXIMIZED MR

1. PERFORMANCE DATA SUPPLIED BY AEROJET
2. PERFORMANCE DATA SUPPLIED BY ROCKETDYNE

Two new vehicles were designed for each of the above propellants to evaluate the performance of space based and ground based vehicles. Space based vehicles were designed for minimum weight. Ground based vehicles were designed for minimum length. All vehicles were designed for the same mission: Perigee Kick delivery of 13,200 lb of useful cargo at Geosynchronous Orbit.

A comparison of the performance of ground based AOTV's is shown in Figure 2.1-7. The highest number of STS flights was needed by the cryogenic LO_2/LH_2 propellants. A general explanation for this surprising result is that these vehicles (which fly on every STS launch) are 50% longer than their storable counterparts. Of the better performing propellants, $\text{N}_2\text{O}_4/\text{MMH}$ is preferred. It requires minimal technology development, and, an infrastructure for handling $\text{N}_2\text{O}_4/\text{MMH}$ exists at all STS launch sites (KSC and VAFB).

The performance of space based AOTV's is compared on Figure 2.1-8. Two different sets of AOTV's are compared in this figure. The upper set of 4 AOTV's, "GB", is a comparison of 4 vehicles (using 4 different propellant systems) which have ground based operational capability, but were used exclusively in a space based mode for this comparison. The second set of 4 vehicles, "SB", were designed as very lightweight space-based-only vehicles. Both sets of vehicles produced similar results. The best performance was obtained with LO_2/LH_2 , which saved between 1 and 2 STS flights per year when compared with all storable propellant vehicles. The superior performance of LO_2/LH_2 is obtained at some cost relative to storables. Before an impartial selection of a totally space based AOTV can be done, a higher quality estimate of the relative cost of obtaining this capability should be performed. The lower part of Figure 2.1-8 indicates most of the significant cost issues that should be addressed.

We have performed an estimate of the relative costs of providing space basing capability for 4 different propellant systems. The results of our coarse analysis are shown on Figure 2.1-9: based upon a 6 year cost cycle, $\text{N}_2\text{O}_4/\text{MMH}$ saved about \$100M when compared with LO_2/LH_2 , even though the LO_2/LH_2 system required 12 fewer STS launches (at \$84M per launch).

Based upon our level of knowledge at this time, we make the following recommendations with respect to selection of a propellant system for the next AOTV:

- At this time, $\text{N}_2\text{O}_4/\text{MMH}$ is the preferred propellant for all basing modes
- The economic consequences of various propellant options should be examined in greater detail
 - Consideration of the effects of manned missions, and the use of storable propellants for these missions, should be factored into the overall economic analysis

2.1.7 Propulsion Subsystem - AOTV Configuration Interactions

The advantages of employing small LOX-H_2 propellant

FIGURE 2.1-7 STUDY RESULTS: OTV PROPELLANT SELECTION

- COMPARED 2 SETS OF OTVs WITH 4 DIFFERENT PROPELLANTS IN BOTH GROUND & SPACE BASED MODES
 - EACH SET CONTAINED 4 VEHICLES, OPTIMIZED FOR THAT BASING MODE, & THE PROPELLANT/ ENGINES THAT WE HAD DATA ON

GROUND BASED VEHICLES (BASING MODE - 1):

| VEHICLE | PERIGEE KICK OPERATION MODE | | | MODIFIED PK OPERATION MODE: ALL PAYLOADS FLY PERIGEE KICK | | |
|--------------------------------------|-----------------------------|-----------------|-------------------------------|--|---------------|------------|
| | # OF PAYLOADS FLOWN | | # OF PAYLOADS THAT DO NOT FLY | # OF PAYLOADS FLOWN | # OF STS FLTS | Δ STS FLTS |
| | "GOOD FIT" OUTPUT* | ADJUSTED OUTPUT | | | | |
| 10-LO ₂ /LH ₂ | 162 | 174 | 2 | 176 | 93 | 0.3 |
| 3-LO ₂ /MMH | 161 | 164 | 12 | 176 | 90 | 0 |
| 7-N ₂ O ₄ /MMH | 161 | 162 | 14 | 176 | 90 | 0 |
| 6-N ₂ F ₄ /MMH | 160 | 163 | 13 | 176 | 89 | -1 |

*PROGRAM LOGIC, NOT STS ON OTV CAPACITY, PREVENTED 17 TO 19 PAYLOADS FROM BEING MANIFESTED

- CONCLUSIONS
 - ALL GROUND BASE "STORABLES" OUTPERFORMED LO₂/LH₂
 - N₂O₄/MMH IS PREFERRED
 - LOWEST DEVELOPMENT COST
 - LEAST EXPENSIVE WAY OF SATISFYING MILITARY DESIRE FOR ON-DEMAND LAUNCH
 - SAME PROPELLANTS ON OMV

FIGURE 2.1-8 STUDY RESULTS: OTV PROPELLANT SELECTION (CONT)

SPACE BASED OTVs (BASING MODE - 4):

| | | "GOOD FIT" OUTPUT, PERIGEE KICK MODE | | | |
|---------|--|--------------------------------------|---------------|------------|----------|
| VEHICLE | | # OF PAYLOADS FLOWN | # OF STS FLTS | Δ STS FLTS | |
| GB | 10-LO ₂ /LH ₂ | 176 | 86 14/YEAR | 0 | |
| | 3-LO ₂ /MMH | 176 | 95 | 0.9 | 1-1/2/YR |
| | 7-N ₂ O ₄ /MMH | 176 | 98 16/YEAR | 1.2 | 2/YR |
| | 6-N ₂ F ₄ /N ₂ H ₄ | 176 | 92 | 0.6 | 1/YR |
| SB | 11-LO ₂ /LH ₂ | 176 | 85 | 0 | |
| | 4-LO ₂ /MMH | 176 | 93 | 0.8 | 1-1/3/YR |
| | 8-N ₂ O ₄ /MMH | 176 | 96 | 1.1 | 2/YR |
| | 7-N ₂ F ₄ /N ₂ H ₄ | 176 | 92 | 0.7 | 1/YR |

- CONCLUSIONS
 - SIGNIFICANT ADVANTAGE OF LO₂/LH₂ OVER N₂O₄/MMH
 - NOT SO SIGNIFICANT ADVANTAGE OF LO₂/LH₂ OVER N₂F₄/N₂H₄
 - FURTHER ANALYSIS IS REQUIRED
 - NEW ENGINE DEVELOPMENT COST
 - COST OF ADDITIONAL STS FLIGHTS
 - COST OF STORING & TRANSFERING CRYO HYDROGEN @ SS
 - COST OF STORING & TRANSFERING CRYO OXYGEN @ SS
 - COST OF STORING & TRANSFERING CRYO N₂F₄ @ SS

engines with I_{sp} in the 480-490 seconds was explored in Phase I of this study. A number of AOTV configuration-engine interaction questions/issues were raised during Phase I, which resulted in about 50% of the Phase II effort being devoted to answering these questions/issues.

The primary tasks in this propulsion subsystem area involved:

- Review of CG offset expectations and recommendation for engine gimbal/hinge requirements for a man rated AOTV.
- Prediction of AOTV base flow field wake closure and the local heat transfer in the separated flow region during re-entry.
- Recommendation of number of engines, engine thrust, and amount of aeroshell protection required.
- Evaluation of some of the proposed advanced engine nozzles re their capability to survive Shuttle Orbiter launch.

2.1.7.1 Engine Nozzle Gimbal/Hinge Requirements

The gimbal angle requirements for the AOTV are strongly influenced by vehicle redundancy level requirements, the number of main engines, and vehicle basing mode.

In all cases the vehicles studied have been designed to a two failure tolerant (fail safe/fail safe) level on the propulsion system. This requires that the vehicle be able to return to a LEO parking orbit after, in the worst case, two engine failures. In Table 2.1-6, the column labeled Gimbal Angle is the maximum angular motion required by the engine's gimbal drive for a worst case vehicle C.M. offset condition. Two conclusions can be reached by analyzing the entries in Table 2.1-6. First, increasing the number of engines on the vehicle reduces the required gimbal angle range. Second, that ground based vehicles require a greater gimbal angle capability than space based vehicles (for vehicle concepts tailored to the same design reference mission).

Ground based vehicles were designed to a minimum length criteria in our study and, in general, had their centers of mass (CM) further aft due to vehicle packaging considerations. The very aft C.M. on the ground based vehicles led to the extremely high gimbal angle requirements for these vehicles. These requirements were as high as 70° for one ground based vehicle, as compared to 2° for a large space based 6 engine cargo delivery vehicle.

The data suggests that the six engine configuration with

FIGURE 2.1-9. OTV PROPELLANT SELECTION (CONCLUDED)

SPACE BASED OTVs (CONT):

- SWAG AT ABOVE ANALYSIS PRODUCED FOLLOWING RANKING, WITH TOTAL COSTS FOR 6 YEARS OF FLIGHT • DDT & E, OF \$1B
 1. $N_2O_4/MMH \rightarrow$ LOWEST COST
 2. LO_2/MMH • 9%
 3. LO_2/LH_2 • 10%
 4. N_2F_4 • 19%
- CONCLUSIONS
 - ECONOMIC JUSTIFICATION REQUIRES MORE DETAILED STUDY OF SPACE BASED OPERATIONS
 - PROPELLANT STORAGE & HANDLING
 - AT THIS TIME, N_2O_4/MMH IS PREFERRED

GROUND BASED & SPACE BASED PROPELLANT SELECTION:

- AT THIS TIME, N_2O_4/MMH IS RECOMMENDED FOR CARGO OTV
 - LOWEST UP FRONT COSTS
 - DEVELOPMENT
 - EARLY YEARS OF OPERATION, WHICH WILL INCLUDE MANY GROUND BASED MISSIONS
 - MOST COMPATIBLE WITH MILITARY NEEDS

QUALIFICATION:

- MANNED MISSIONS WERE NOT CONSIDERED IN THIS MANIFESTING STUDY
- OTHER WORK HAS SHOWN A SAVINGS OF 1 STB FLT/MANNED MISSION WITH A SMALL CREW CAPSULE ("BARE BONES") AND SMALL, HIGH I_{sp} LO_2/LH_2 ENGINES

TABLE 2.1-6. GIMBAL ANGLE REQUIRED FOR FAILSAFE/FAILSAFE OPERATION

| NUMBER OF ENGINES | VEHICLE | GIMBAL ANGLE | BASING MODE |
|-------------------|---------------------|--------------|--------------|
| 3 | 11 - LO_2/LH_2 | 15.5° | SPACE BASED |
| 3 | 4 - LO_2/MMH | 22.4° | |
| 3 | 8 - N_2O_4/MMH | 9.1° | |
| 4 | 7 - N_2F_4/N_2H_4 | 19.4° | |
| 6 | 4 - LO_2/LH_2 | 2.0° | |
| 3 | 10 - LO_2/LH_2 | 46.6° | GROUND BASED |
| 3 | 3 - LO_2/MMH | 70.0° | |
| 3 | 7 - N_2O_4/MMH | 55.0° | |
| 3 | 6 - N_2F_4/N_2H_4 | 57.6° | |
| 6 | 1M - LO_2/LH_2 | 4.0° | |

- SPACE BASED VEHICLES REQUIRE SMALLER GIMBAL ANGLES THAN THEIR GROUND BASED COUNTERPARTS.
- INCREASING THE NUMBER OF ENGINES REDUCES THE GIMBAL ANGLE REQUIREMENTS DURING ENGINE OUT CONDITIONS

hinged engines is a very attractive method of obtaining required safe return from HEO's after multiple failures without having to contend with very large gimbal angle requirements. Benefits occur in both engine and vehicle design.

2.1.7.2 Base Flowfield Wake Closure and Separated Flow Heat Transfer

Employing a historical laminar flow base pressure data base for sharp and blunt cones, and results from the GE 3D Viscous Boundary Layer Code (3VFF), local pressure in the base area was estimated and flow turning angles computed on the basis of a Prandtl Meyer type expansion from the local windward flow into the base area.

This turning angle varies throughout the entry maneuver and is mostly altitude dependent for this class of vehicles, being larger, approximately 48° , at the higher altitudes.

With these variations, employing current state-of-the-art wake closure knowledge, it is recommended that the engine nozzles extend aft of the AOTV fuselage only far enough for plume clearance. With an improved state of knowledge, e.g., calibration of numerical modeling (CFD) efforts, more ground tests, and continuing evaluation of STS flight test results, and an AOTV flight test, it is expected that the nozzles could be extended aft some distance into the separated flow region. The wake closure streamline is expected to deflect $\sim 30^\circ$ from an extension of the AOTV windward meridian.

Employing the heat transfer amplification magnitudes experienced by the SSME nozzles of the STS orbiter, estimates have been made of the local temperatures on the engine nozzle with and without body flap induced shock impingement, Table 2.1-7. The heat transfer to the relatively quiescent flat base area has been estimated employing a flight test derived algorithm. The presence of the protruding nozzles results in an increase in heat transfer, as does the local impingement of body flap generated trailing shock systems. Local surface temperature predictions have been made based on a surface emittance of 0.8, a view factor to space of 0.5, and local radiation equilibrium. It is seen that trailing flap induced shock impingement on the nozzles clearly must be avoided.

A recommended approach would also employ control flaps placed on the body rather than trailing. Technology development implications involve use of CFD, ground tests, and continuing evaluation of STS orbiter flight results.

2.1.7.3 Number of Engines and Engine Thrust

Over the four years of this contract, we have extensively studied the effect of varying the size of a fail

safe/fail safe LO_2/LH_2 main propulsion system's engines, while keeping the total thrust of a vehicle constant (15,000 lbs, a representative value for the class of missions we have studied).

The studies fall into two general categories:

- Parametric trending of subsystem and vehicle characteristics, and,
- Comparison of discrete point designs in a manifesting study.

While the manifesting study results for cargo vehicles contradicts the parametric results for cargo vehicles, it reinforces the parametric results for manned vehicles (like H-1M).

For vehicle which require full aeroshell protection out to the end of the nozzle, the weight of additional structure and propellant makes the significant difference in start of mission weight which is shown in Figure 2.1-10 (the non-shaded bar graph). Since the 'weight penalty at mission start' (the ordinate of the figure) is strongly related to deliverable payload, weight penalties above 400 lb are significant. Therefore, for this type of vehicle, we recommend:

- 6 hinged engines of 2500 lb_f thrust each
 - 1 gimbal axis which produces engine motion parallel to the aeroshell

Another type of vehicle was evaluated that has only a small amount of aeroshell protection for the engine nozzles. It requires flight test experience before the required amount of aeroshell protection can be known, but we have assumed values for the purpose of reaching some conclusions now. For this type of vehicle, we recommend:

- 1, 4 or 6 engines of 15,000 lb_f total thrust

Since the amount of thermal protection which is needed at the aft end of a biconic AOTV is unknown nose, and, since this class of vehicles can be designed and built without the expense of a flight test program, we have consolidated the above three recommendations into the following recommendation for liquid oxygen-hydrogen engines:

- A manned biconic AOTV should have six hinged low thrust engines

We have also conducted parametric analyses of "man-rated" cargo carrying vehicles. These vehicles differ from the manned vehicle by being substantially smaller, since their internal tankage was sized for delivering a "typical" GEO payload



TABLE 2.1-7

SUMMARY OF ENGINE NOZZLE HEAT TRANSFER RESULTS

| LOCATION | TEMPERATURE (°F) FOR $\epsilon = 0.8$, $\mathcal{F}_A = 0.5$ |
|--|--|
| RELATIVELY QUIESCENT BASE AREA | 480 |
| ON PROTRUDING ENGINE NOZZLE | 1120 |
| ON NOZZLE WITH SHOCK IMPINGEMENT | 1770 |
| ON NOZZLE WITH SHOCK IMPINGEMENT WITH $X/2P_B$ UNCERTAINTY | 2300 |

AOTV IMPLICATIONS

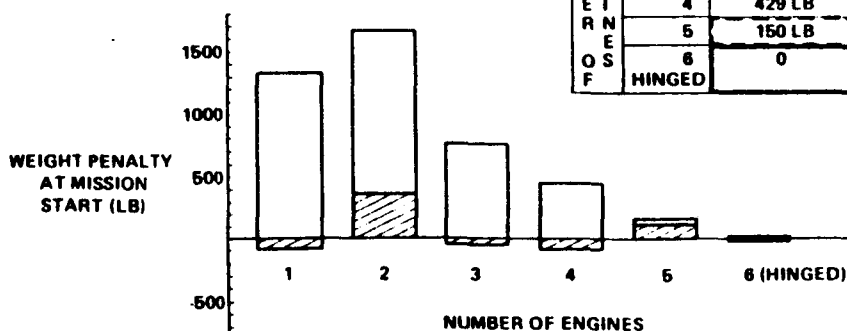
- o SHOCK IMPINGEMENT MUST BE AVOIDED
- o SUPPORTS CASE FOR MULTIPLE SMALL ENGINES
- o CONTROL FLAPS SHOULD BE ON BODY NOT TRAILING
- o TECHNOLOGY NEEDS:
 - APPLICATION OF CFD AND CALIBRATION OF METHODOLOGY
 - LOW REYS, HIGH M_∞ GROUND TESTS
 - CONTINUING EVALUATION OF STS RESULTS

TABLE 2.1-10. WEIGHT PENALTY AT START OF MISSION
vs NUMBER OF ENGINES

- FAILSAFE/FAILSAFE AOTV
- 1500 LBF TOTAL THRUST
- AEROJET ENGINE DATA
- 3" C.M. OFFSET EFFECTS
 - ENGINE THROTTLING PENALTIES + INCREASED GRAVITY LOSS INCLUDED
 - SINGLE PERIGEE BURN, SINGLE STAGE TO GEO & BACK

INCLUDES AEROSHELL WEIGHT
FROM PHASE I STUDY

AOTV WEIGHT NOT EFFECTED
BY ENGINE LENGTH



| | | INCLUDES AEROSHELL WEIGHT FROM PHASE I STUDY | AOTV WEIGHT NOT EFFECTED BY ENGINE LENGTH |
|---|-------------|--|--|
| N U E M N B G E I R N E O S F | 1 | 1325 LB | -70 LB |
| | 2 | 1678 LB | 346 LB |
| | 3 | 742 LB | -17 LB |
| | 4 | 429 LB | -70 LB |
| | 5 | 150 LB | 128 LB |
| | 6 HINGED | 0 | 0 |

of 13,200 lb via a perigee kick delivery mode. The study results produced the following recommendation for LH_2 - LH_2 propulsion:

- A man rated "small" cargo vehicle should utilize 4 engines of 3000 lb_f thrust each

Our manifesting study compared the number of orbiter flights required to deliver all payloads in a 6 year mission model. As discussed in Paragraph 2.1.4 and shown on Figure 2.1-11, an economic advantage is obtained from using large, high thrust vehicles. While this contradicts the trending analysis (which assumes that every pound of unnecessary vehicle weight will cost a significant amount of money for propellant for every AOTV flight), we believe the modeling of real world STS cargo packaging constraints represents a more accurate description of transportation costs. Consequently, our recommendation for LO_2 - LH_2 powered man rated cargo carrying vehicles is:

- 6 engines of 3000 lb_f thrust each

2.1.7.4 Aeroshell Protection Required for Nozzles

Current state of knowledge of AOTV base flow field wake closure and the local heat transfer in the separated flow region was examined in Paragraph 3.3.1.2. Figure 2.1-12 displays two vehicle arrangements which are based upon the results of Paragraph 2.1.7.2. The upper vehicle indicates that a single medium thrust, high expansion ratio nozzle engine can be entirely contained within the low heating zone (defined by the 30° angle from the aft frustum line) without any aeroshell extending beyond the gimbal station of the engine. Similarly, the lower vehicle shows that 3 high expansion ratio nozzles, on low thrust engines, also fit within the protected zone without extending the aeroshell beyond the engines' gimbal plane. Thus, if AOTV flight test data indicate that thermal effects within the "protected zone" are as we anticipate, biconic AOTVs can reduce their structure and TPS weights by a few hundred pounds.

2.2 Summary of Major Technology Benefits

The major technology benefits identified for Space Based AOTVs include the following:

- Automation of routine AOTV inspection and maintenance was identified as the only enabling technology for a Space Based AOTV.
- Numerous enhancing technology areas were identified that can provide substantial transport cost reduction. These include 1) improved life time of storable propellant engine, 2) avionics weight reduction, 3) external thermal protection system (TPS) weight reduction by: a) reducing the coating

FIGURE 2.1-11 **STUDY RESULTS: LARGE vs SMALL OTV**

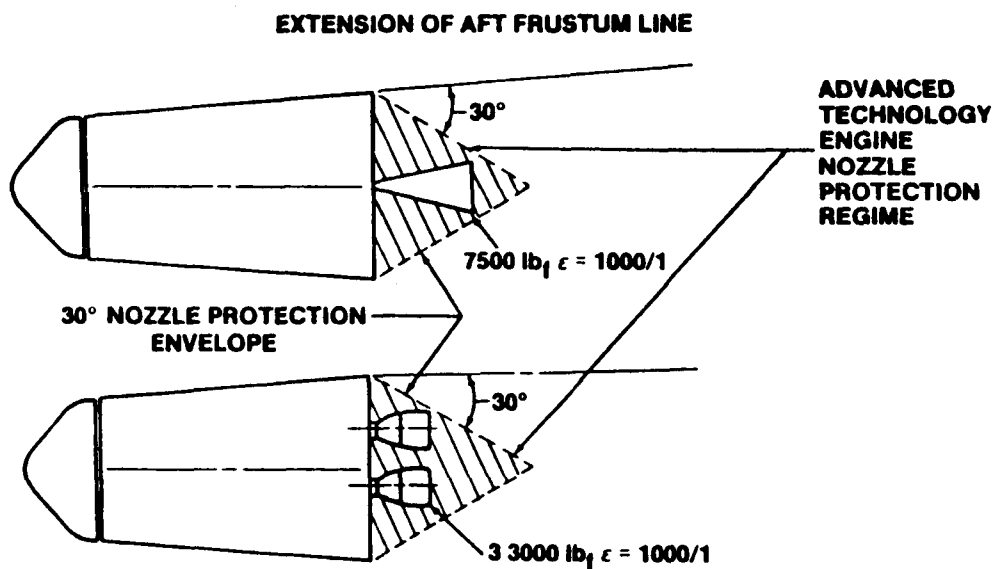
- **LARGE OTV (V8 = 4-LO₂/LH₂) DESIGNED FOR 14K UP & BACK MANNED MISSION**
 - DRY WEIGHT = 7000 LBS
 - TOTAL THRUST = 18000 LBS
 - I_{sp} = 480 SEC
- **SMALL OTV (V20 = 11-LO₂/LH₂) DESIGNED FOR "NOMINAL" CARGO DELIVERY (13,200 LB USEFUL AT GEO) WITH PERIGEE KICK DELIVERY**
 - DRY WEIGHT = 5725 LBS
 - TOTAL THRUST = 9000 LBS
 - I_{sp} = 480 SEC
- **COMPARISON OF VEHICLES IN CARGO DELIVERY ROLE**
 - SPACE BASED
 - PERIGEE KICK OPERATIONS

| <u>VEHICLE</u> | <u># OF OTV FLTS</u> | <u># OF STS FLTS</u> |
|---------------------------------------|----------------------|----------------------|
| 4-LO ₂ /LH ₂ | 37 | 85 |
| 11-LO ₂ /LH ₂ * | 41 | 85 |

*REQUIRES EXTERNAL TANKS FOR 14 MISSIONS

- **CONCLUSIONS**
 - FEWER OTV FLTS PROVIDE SMALL ENGINE LIFE ADVANTAGE TO LARGER VEHICLE
 - IF EXTERNAL TANKS MUST BE DROP TANKS, LARGE VEHICLE SAVES ~ \$210M OVER 6 YEARS

FIGURE 2.1-12 **BICONIC AFT ENGINE DESIGN OPTION**



- **VEHICLE WEIGHT SAVINGS WITH CENTRALLY LOCATED ENGINES**
- **FLIGHT TEST DATA REQUIRED BEFORE THIS DESIGN TECHNIQUE CAN BE USED**



0263-0114P

weight, b) further reducing the non-catalytic nature of the coating, increasing the maximum allowable bond/structure temperature, 4) decrease of uncertainties in aerodynamic and aerothermodynamic performance, 5) electrical power subsystem weight reduction due to incorporation of advanced materials and 6) reducing the structural shell weight by improving the quality of the design allowable data and use of advanced structural materials.

- Advanced aerothermodynamic methodology and aft end configuring may provide enlarged allowable zone for engine nozzle protrusions into the separated flow region.
- Payload manifesting at Space Station is recommended.
- Space Station propellant manifesting is recommended for all propellants except liquid hydrogen.

2.3 Recommendations for Further Study

Based on the results of this study, further work is recommended in the following areas:

- 1) An evaluation should be conducted of the N_2O_4 -MMH reusable engine needs.
- 2) Economic consequences of various propellant options should be examined in greater detail including the effects of manned missions.